# A ONE-NANOSECOND X-BAND RADIO-FREQUENCY PULSE GENERATOR USING A GUNN DIODE OSCILLATOR AND AVALANCHE TRANSISTOR MODULATOR

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# THESIS

A ONE-NANOSECOND X-BAND RADIO-FREQUENCY PULSE GENERATOR USING A GUNN DIODE OSCILLATOR AND AVALANCHE TRANSISTOR MODULATOR

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A One-Nanosecond X-Band Radio-Frequency
Pulse Generator Using a Gunn Diode Oscillator
and Avalanche Transistor Modulator

by

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ABSTRACT

A simple circuit has been developed for producing extremely short X-band radio-frequency pulses using a Gunn-effect oscillator and avalanche transistor modulator. Construction techniques and some resulting difficulties are discussed. Representative pulses on the order of 1 nanosecond and 30 milliwatts at 8.5 gigahertz are presented.

This circuit is intended for use in waveguide time-domain reflectometry. The nanosecond pulses offer a large improvement in resolution over previous pulse generation systems.

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# I. INTRODUCTION

In 1968 Shoemaker [Ref. 1] submitted a thesis on the use of very short RF pulses for waveguide fault-finding by time-domain reflectometry (TDR) techniques. By modulating the grid of a traveling-wave tube he was able to obtain 50-mW pulses with a duration of 10 nsec as measured at the half-power points. As shown in Fig. 1 the resolution of these pulses was about 1.5 meters.

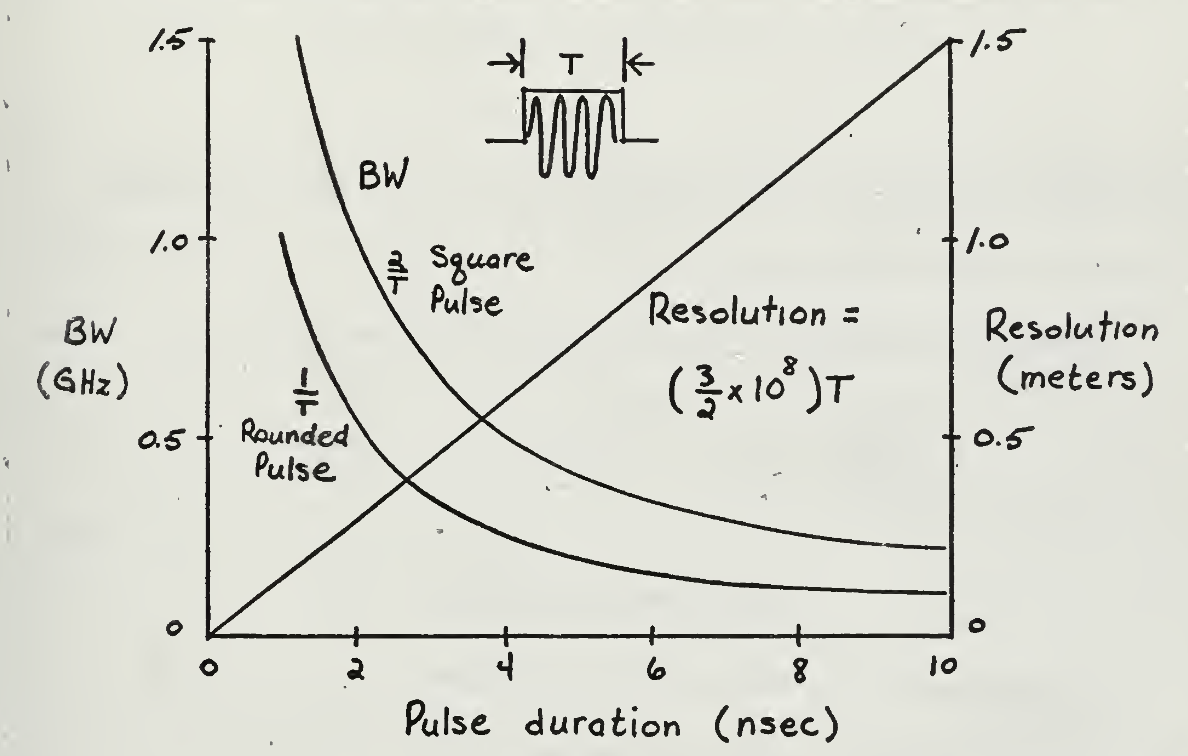


Figure 1. Bandwidth and resolution as a function of pulse duration.

The object of this thesis is to describe a method for generating RF pulses as short as 1 nsec in duration. In practice, since the required bandwidth increases rapidly as the pulse becomes very narrow, the carrier frequency and waveguide will set a lower limit on the length of pulse that may be used in TDR.

Figure 2 shows the dimensions and principal cut-off frequencies

of RG-52/U waveguide which is designed to operate in X-band.

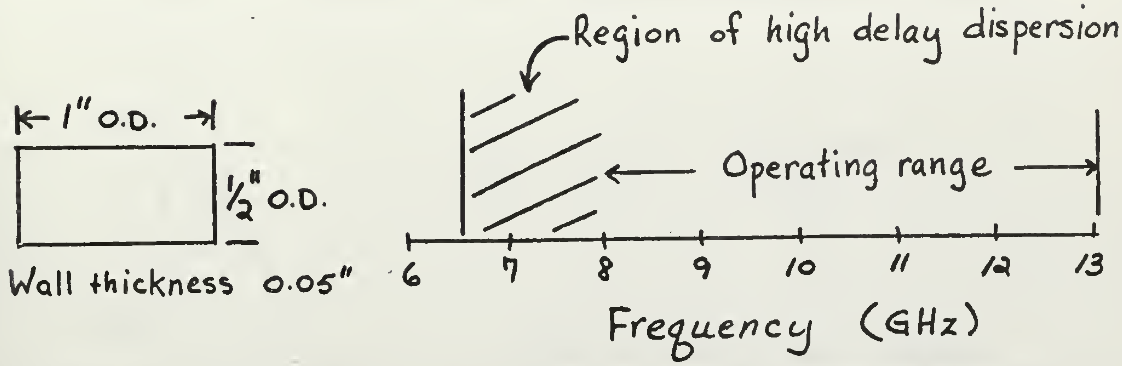


Figure 2. Characteristics of RG-52/U waveguide.

Karbowiak [Ref. 2] gives an equation (1) for the maximum bandwidth allowed by delay distortion. For pulse modulation one radian of phase delay is assumed to be permitted between the carrier and sidebands.

$$BW = 19.5\left(\frac{f}{F}\right)\left(\frac{f}{L}\right)^{\frac{1}{2}} \tag{1}$$

where

BW = pulse bandwidth in MHz

f = carrier frequency in GHz

F = cutoff frequency in GHz

L = effective waveguide length in km

Note that for a reflected pulse the effective waveguide length is twice the physical length. Figure 3 is a plot of equation (1) for selected values of carrier frequency. As an example, if f = 10 GHz and the effective waveguide length is 50 m then 520 MHz of bandwidth is permitted. Referring to Fig. 1 this is equivalent to a square pulse of 4.7-nsec duration (0.7 m resolution) or a rounded pulse of 2.3-nsec

duration (0.35 m resolution). Some delay distortion is probably acceptable in practice if an improvement in apparent resolution is desired.

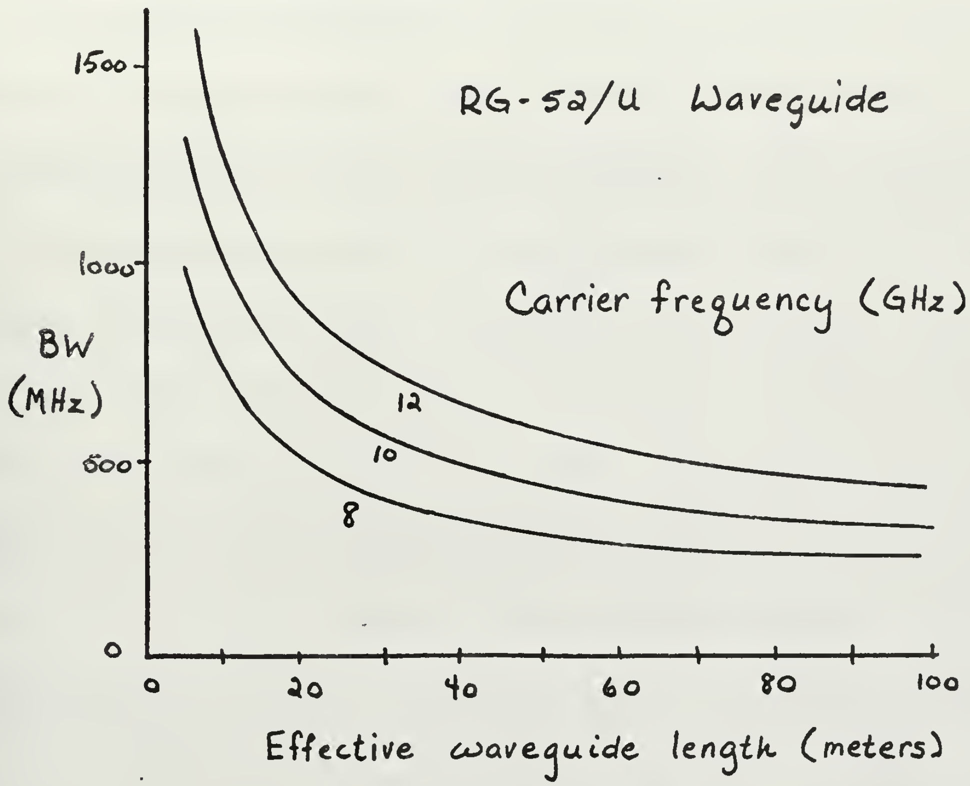


Figure 3. Maximum pulse bandwidth permitted by delay distortion.

# II. WAVEGUIDE CAVITY

## A. BULK NEGATIVE-RESISTANCE DEVICES

A Gunn-effect (bulk negative-resistance) device was selected to be the source of the RF carrier. There are several reasons why this device is particularly suited for this type of application. First, the device is very small which allows it to be mounted inside a section of waveguide. Second, it needs only simple circuitry to operate properly. Third, although its output power is low during continuous operation - thermal dissipation limits it to the milliwatt range - peak power on the order of several watts is easily attainable when the device is pulse modulated with a low duty cycle. Fourth, and perhaps most important, the device (also referred to as a Gunn diode) switches on and off very rapidly. When an applied voltage crosses a threshold level, the diode begins oscillating at the transit time frequency with a substantial output. When the applied voltage drops below the sustaining level, the device stops oscillating immediately. Thus under pulsed conditions the rise and decay times of the RF envelope are determined almost solely by the Q of the external circuit. If this is kept very low then pulses with rise and fall times less than 1 nsec are possible.

In recent years numerous reports have been published on the properties of bulk negative-resistance devices. For additional information the reader is referred to the literature and, in particular, the book edited by Watson [Ref. 3].

The Gunn-effect devices used in this research were provided by

Associates Inc. They were rated at a minimum of 20 mW CW with transit time frequencies about 10 GHz. Each was attached to a small screw for ease in mounting. See Fig. 4.

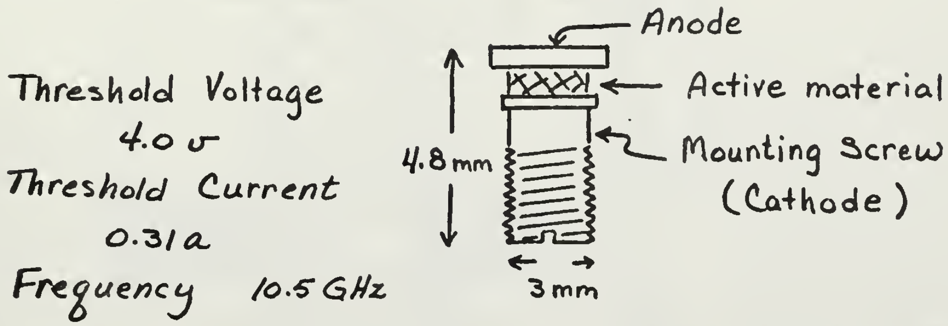


Figure 4. Cross section and characteristics of sample Gunn-effect device.

## B. WAVEGUIDE CAVITY

The device was mounted on a ramp in a section of RG-52/U waveguide as shown in Fig. 5. A moveable short was positioned behind the diode for tuning purposes. The entire waveguide and ramp were kept at dc ground potential; the dc voltage was applied through a moveable contact inserted in a hole in the top of the waveguide. A quarter-wave thick copper block was put around the contact pin and attached to the waveguide so that the contact pin would look like a shorted stub to the RF wave.

## C. CAVITY TUNING

The cavity was tuned for maximum CW output by moving the diode and tuning short alternately. Figure 6 shows the equipment used to monitor the RF power.

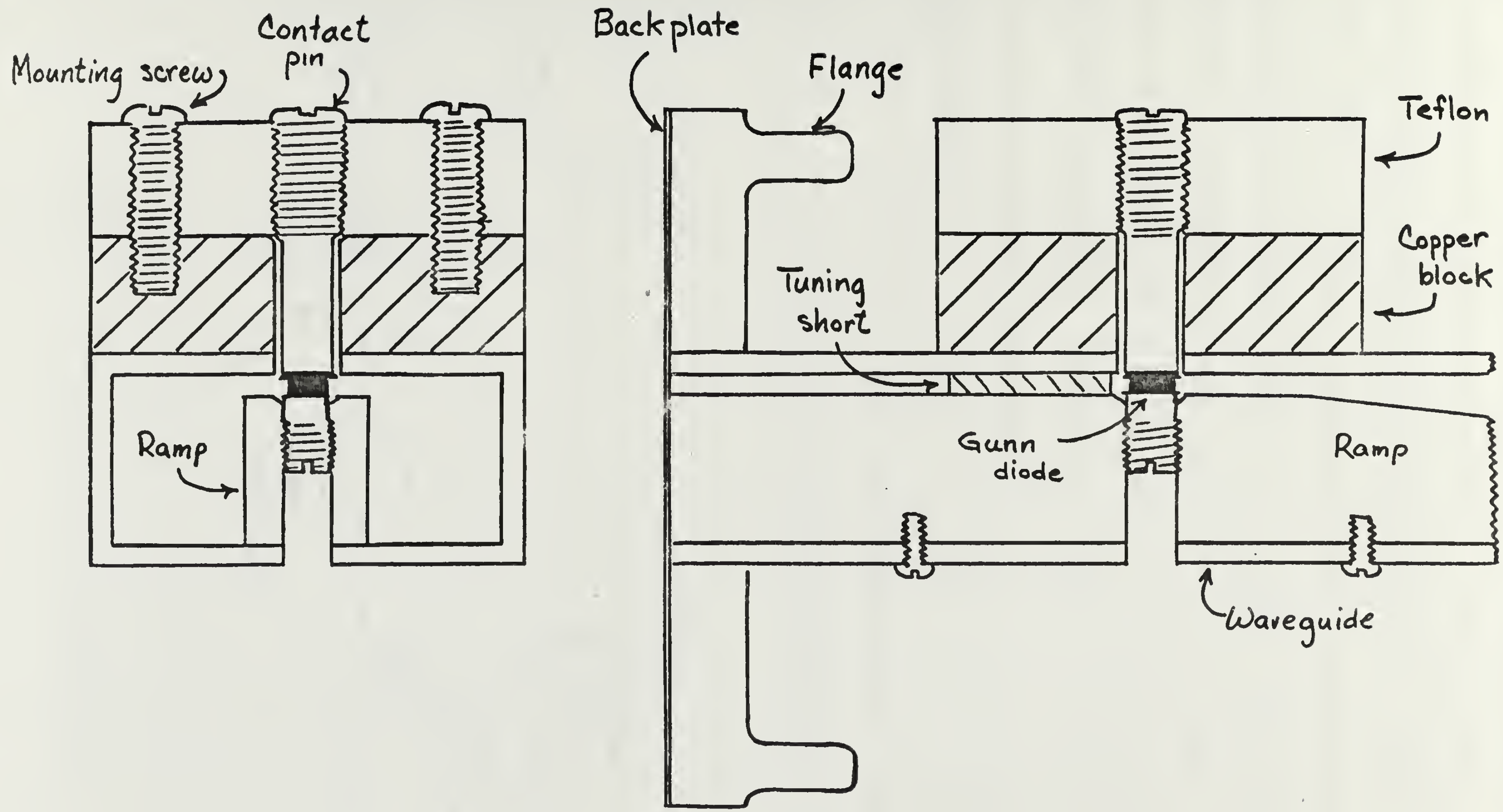


Figure 5. Waveguide cavity.

Three major difficulties were noted. One was the susceptibility of Gunn-effect devices to voltage transients - abruptly breaking the dc circuit was sometimes sufficient to damage a device. Second, an excessive voltage of about 3 volts was sufficient to cause thermal runaway and permanent damage within a few seconds. Third, the moveable short wore very rapidly and soon ceased to function properly. On one occasion 35.2-mW output was attained but subsequent movement of the short made it inoperative. Another short was fabricated but only 2-mW CW output was achieved with the short as close to the diode as possible without touching.

Since all but one of the devices had been damaged it was decided to discontinue CW turning and save the last diode for pulsed operation.

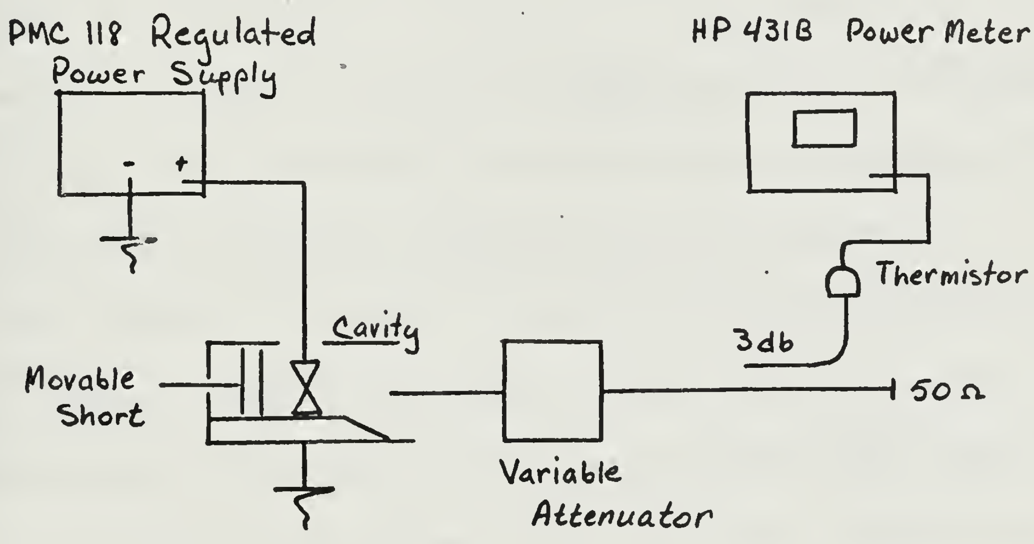


Figure 6. Circuit for tuning waveguide cavity.

## III. DC PULSE GENERATOR

### A. BASIC DESIGN

The most straightforward technique for generating extremely short dc pulses is that of discharging a capacitor through a load. This is shown schematically in Fig. 7.

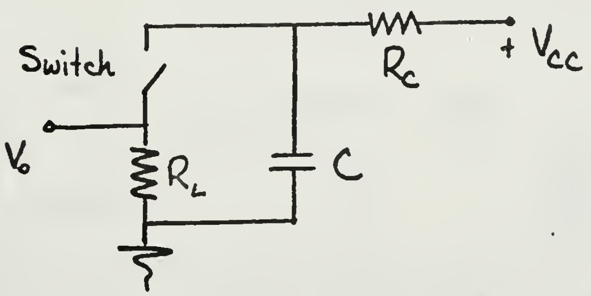


Figure 7. Simple pulse generator.

When the switch is open the capacitor is charged through $R_C$. When the switch is closed the capacitor discharges through $R_L$. The charging resistor $R_C$ must be large enough so that the current flowing through it has no appreciable effect on the pulse when the switch is closed.

As is apparent, the switch is the most critical component in the circuit. Mercury-wetted electromechanical types were first considered since they close very quickly, but they cause pulse-to-pulse jitter and would be difficult to synchronize with an oscilloscope. Silicon transistors operating in the avalanche mode are also extremely fast acting (switching times < 1 nsec) and since substantial material on this subject [Refs. 4, 5, 6] was readily available it was decided to use this type of

device.

## B. SCR SWITCH

The silicon controlled-rectifier is designed to operate in the avalanche mode. A typical circuit is shown in Fig. 8. When a suitable current pulse is applied to the gate the device avalanches and the capacitor discharges through $R_L$ and the dynamic resistance of the device.

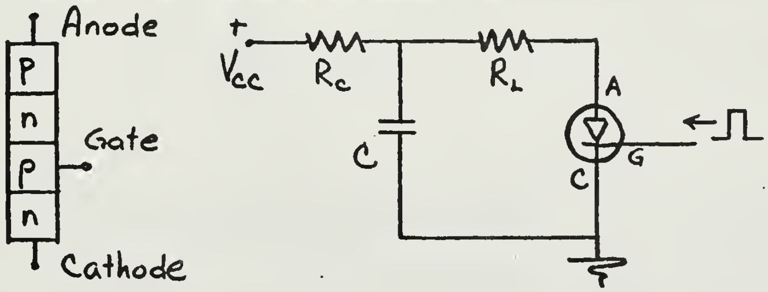


Figure 8. Silicon controlled-rectifier switch.

Note that the load is in the anode side. Apparently if the load is between cathode and ground the current flowing through it raises the potential of the cathode and turns the device off. This type of circuit could have been adapted to the waveguide cavity - which had already been constructed - but it would have meant putting a large negative potential on the waveguide itself. This was considered undesirable. Furthermore, because of its greater charge storage, the turn-off time of the SCR would have been longer than that of the transistor described in paragraph D below so no further work was done with this particular switch.

## C. AVALANCHE DIODE SWITCH

The DIAC or bidirectional avalanche diode is shown in Fig. 9. The

device is basically a p-n-p transistor without the base contact. When a sufficiently large potential is applied to either terminal avalanche breakdown occurs. When this happens in the circuit shown in Fig. 9 the charge stored in the capacitor flows through the DIAC and $R_L$.

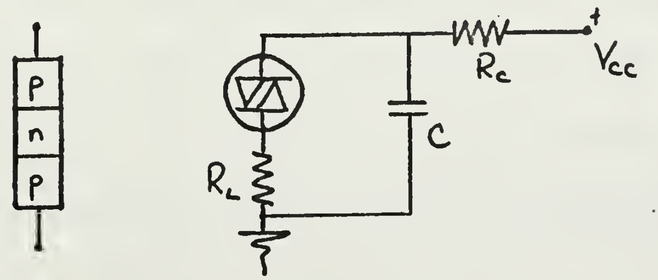


Figure 9. Bidirectional avalanche diode.

Unfortunately most of the voltage drop occurs across the device and not the load. Because of this and potential triggering problems with an oscilloscope the idea was discarded.

## D. BIPOLAR JUNCTION TRANSISTOR SWITCH - AVALANCHE MODE OPERATION

Satisfactory pulses were finally obtained by operating an n-p-n high-voltage switching transistor in the avalanche mode. Hansen [Ref.4] has made a thorough analysis of this type of switch. The circuit required is shown in Fig. 10. The capacitor C is charged to a high voltage through resistor $R_C$. Applying a small positive pulse to the base causes the transistor to avalanche. The capacitor C then discharges through the dynamic avalanche resistance of the transistor and the load $R_L$. $R_C$ must be large enough so that the current flowing through it

during the avalanche does not cause the transistor to exceed its power rating. The maximum pulse repetition rate is determined by whichever is less - the recharging time constant $R_C C$ or the power dissipation ability of the device. The amplitude of the triggering pulses need only be about 1 to 3 volts, depending on $V_{CC}$ and the transistor being used. Excessive amplitude in the trigger pulse is undesirable since it can be detected in the output. The width of the trigger pulse is unimportant because it is first differentiated before being applied to the base.

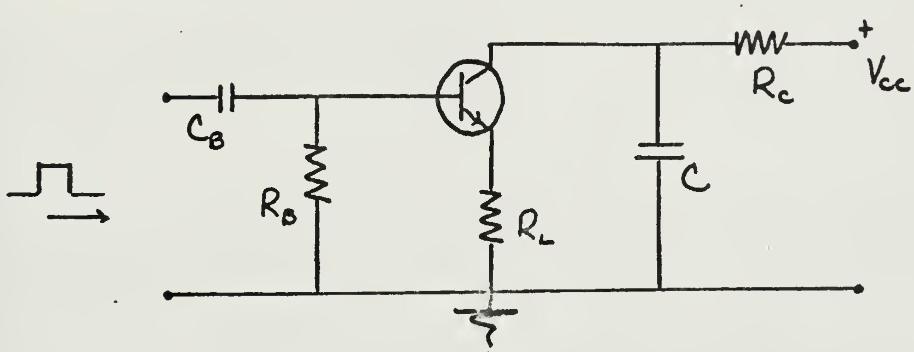


Figure 10. Circuit for operating BJT in avalanche mode.

During avalanche the output circuit, as redrawn in Fig. 11, is essentially a series RLC network. Analysis of the circuit is straightforward and can be found in most elementary textbooks on network theory. The load current I as a function of time is plotted in Fig. 12 for several values of L. The circuit is critically damped when $L = L_C$ as given by equation (2).

$$L_c = \frac{(R_L + r_{ce})^2 \ C}{4} \tag{2}$$

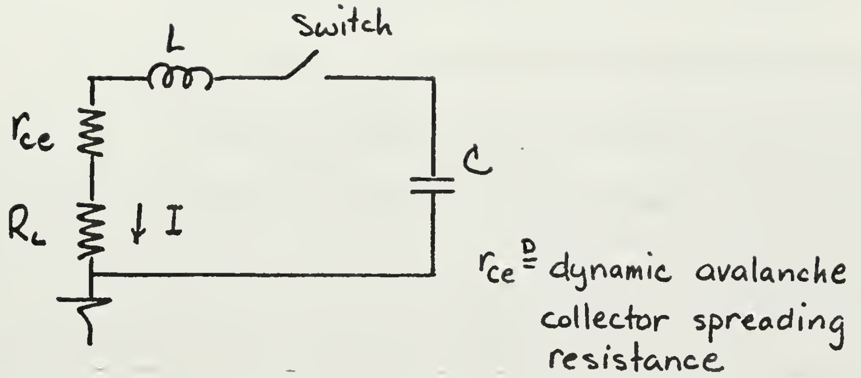


Figure 11. Output circuit as series RLC network.

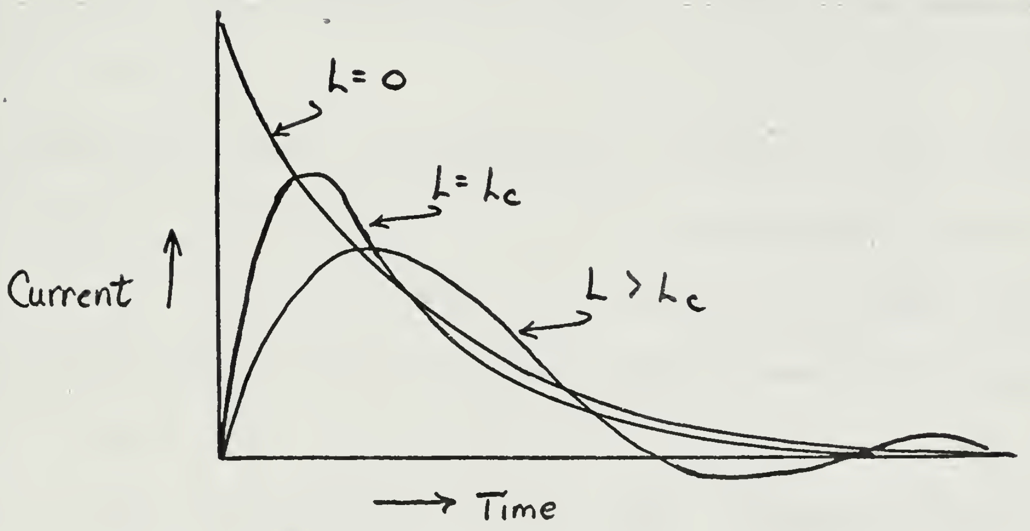


Figure 12. Current waveform in series RLC network.

In general L can be minimized but it is not easily varied. To avoid oscillations either $R_L$ or C must be kept large enough, but this involves a tradeoff. Increasing C broadens the pulse, while increasing $R_L$ decreases the current amplitude (and also causes some broadening). For example, if L = 4 nanosecond and C = 10 picofarads then $(R_L + r_{ce})$ must equal 40 ohms for critical damping. If the pulse is narrowed by decreasing C to 5 picofarads then $(R_L + r_{ce})$ must be increased to 57 ohms.

A transistor in the avalanche mode is operating with $V_{CE}$ between $BV_{CEO}$ and $BV_{CBO}$. These breakdown voltages must be high if the output pulses are to be substantial. A high $\beta$ is also desirable since this is indicative of the ability of a transistor to avalanche properly.

Numerous transistors were tested and only those with a $\beta$ greater than 75 would avalanche quickly and completely.

## E. TEST CIRCUIT

The component values as finally used are given in Fig. 13(a). The complete test circuit is drawn in Fig. 13(b). The Datapulse 101 pulse generator, which was run at 10 KHz, has a variable-delay output which enabled the avalanche pulse to be properly synchronized with the oscilloscope. The Hewlett-Packard sampling oscilloscope has a rise time of 350 picoseconds and a bandpass of dc to 1 GHz. Frequencies beyond that can be detected but they will be attenuated.

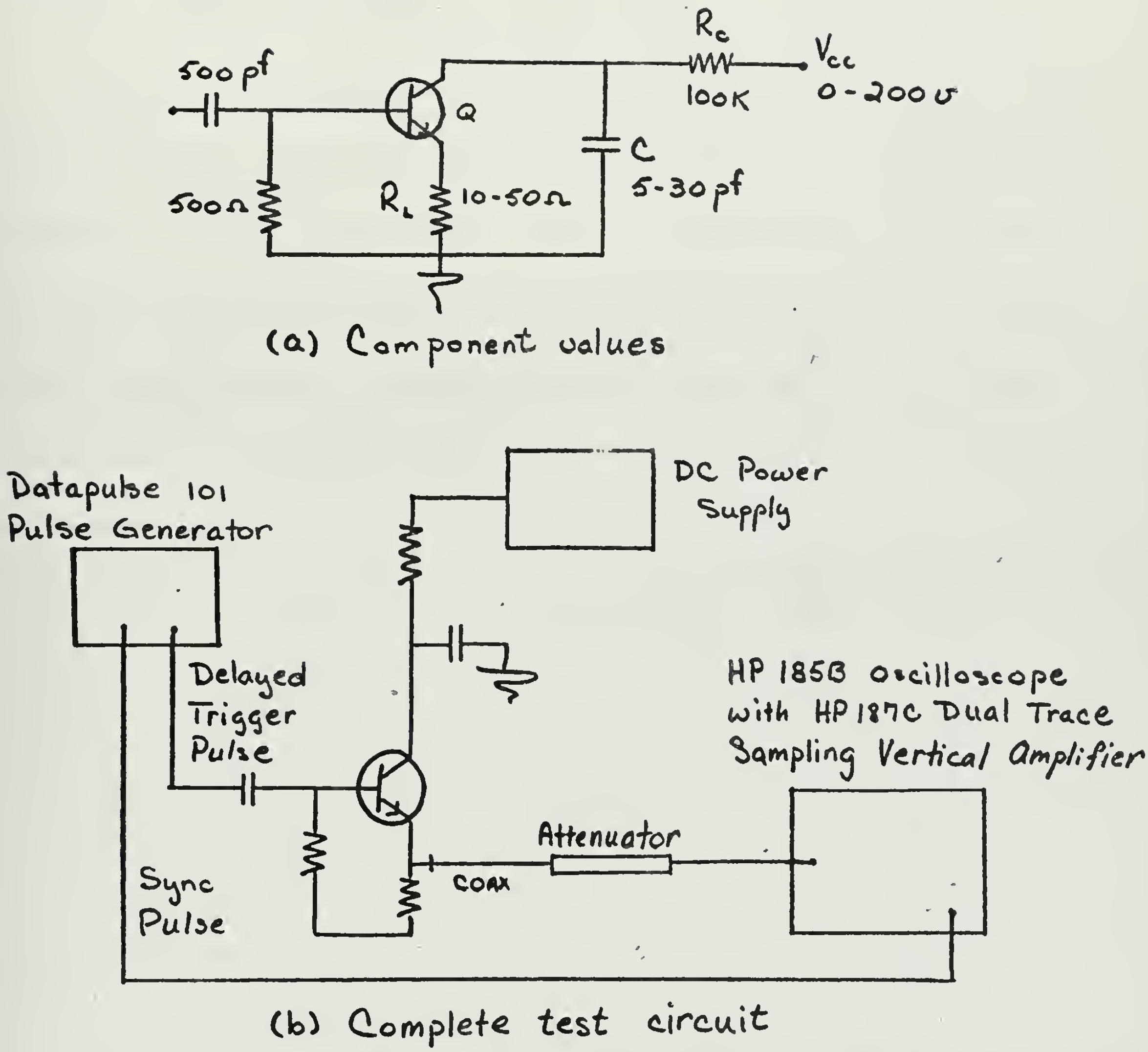


Figure 13. DC pulse generator.

## F. REPRESENTATIVE DC PULSES

A representative sampling of the dc pulses obtained is given in Fig. 14 for different values of $R_L$ and C. Figures 14(a) through 14(e) were generated using an RCA 2N3512 while Fig. 14(f) was with a Motorola HEP 53 (2N 2476).

Not all of the oscillations were due directly to the avalanche circuit. The pulse circuit radiated slightly and this was picked up by the coaxial lead to the oscilloscope. Also, a transition had to be made from the load resistor to the coaxial lead and the resulting mismatch caused distortion and ringing. Nevertheless certain fundamental oscillations can be seen, particularly in Fig. 14 (e), indicating that R, L and C were not properly matched.

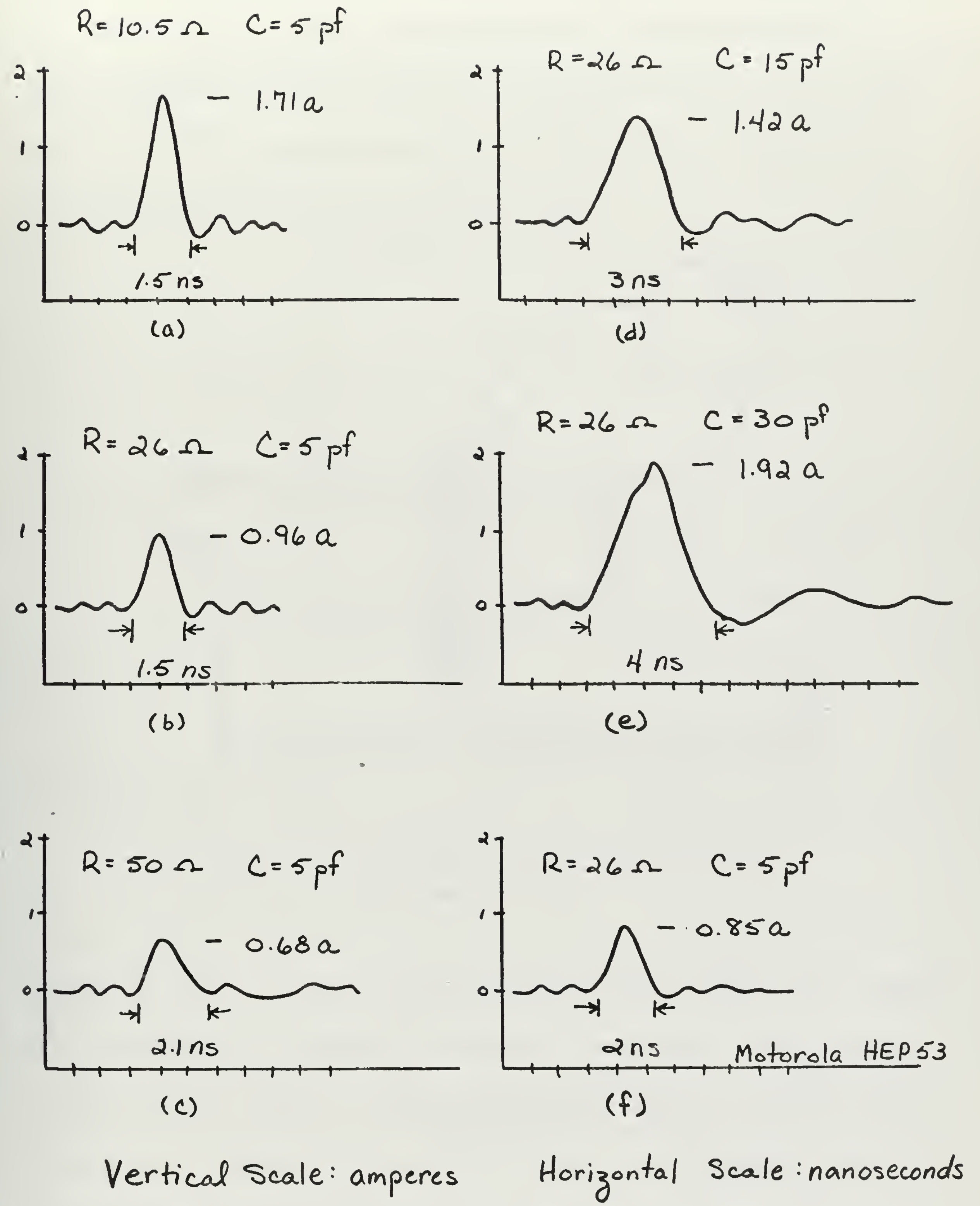


Figure 14. DC pulses (a) - (e) RCA 2N 3512
(f) Motorola HEP 53

## IV. RF PULSE GENERATOR

The RF pulse generator was constructed by superimposing the dc pulse generator directly on top of the waveguide cavity as can be seen in Fig. 15. The equivalent circuit is the same as Fig. 10 except that the Gunn-effect device is in series with $R_L$.

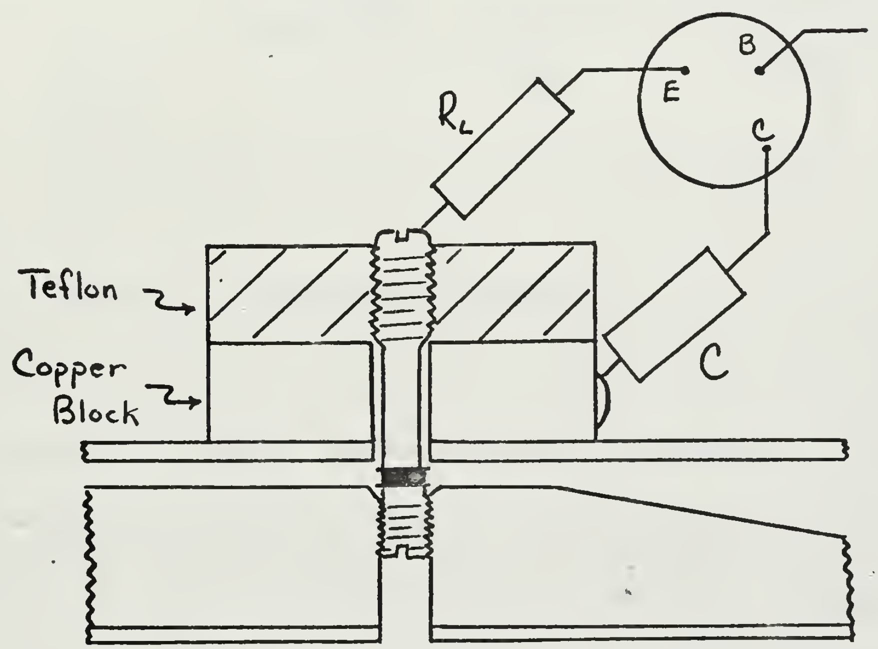


Figure 15. Avalanche pulse generator mounted on waveguide cavity

Figure 16 shows the pulse envelope detector circuit which used a crystal (IN 23 WE) mounted directly in a section of waveguide. Other arrangements were tried using HP 440A and HP X485B detectors but they caused severe pulse distortion and spurious ringing. The calibration curves for the circulator and crystal are given in appendix A.

The RF carrier frequency was obtained by sampling the RF pulse

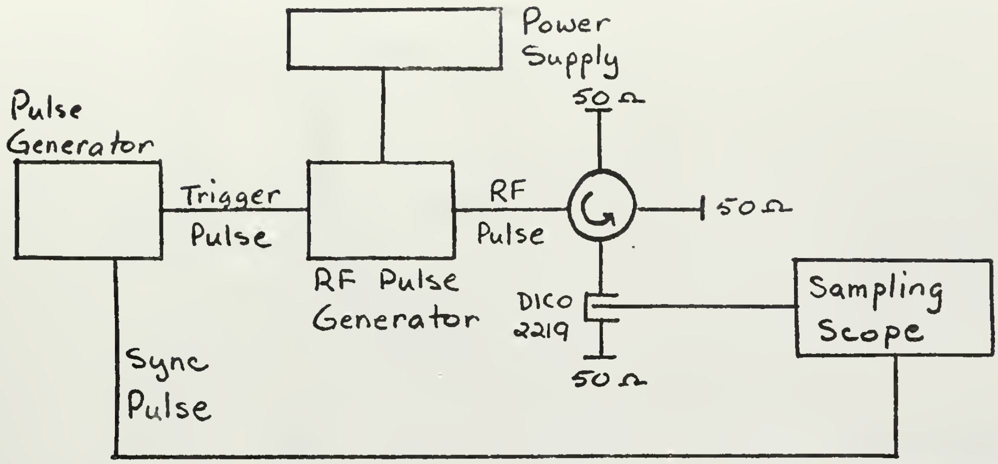


Figure 16. Pulse envelope detector.

directly through a waveguide-to-coax adapter (not shown). The time scale of the oscilloscope was expanded until the individual oscillations of the RF sine wave were observed. From this the carrier frequency was determined to be 8.5 GHz.

Figures 17(a) through 17(f) are the envelopes of the pulses that were obtained with this circuit. In all but one case an RCA 2N3512 was used in the pulse generator. For comparison purposes a Motorola HEP53 was tried; it produced a slightly stronger pulse as seen in Fig. 17(e).

Unlike the dc pulse generator, this circuit was very sensitive to the power supply voltage $V_{CC}$. If $V_{CC}$ was changed by $\pm$ 1v from its optimum value the dc pulse would be outside the operating range of the Gunn diode and it would cease to oscillate. Fig. 17(b) and 17(c) are the same except that $V_{CC}$ was slightly detuned in the latter case. This

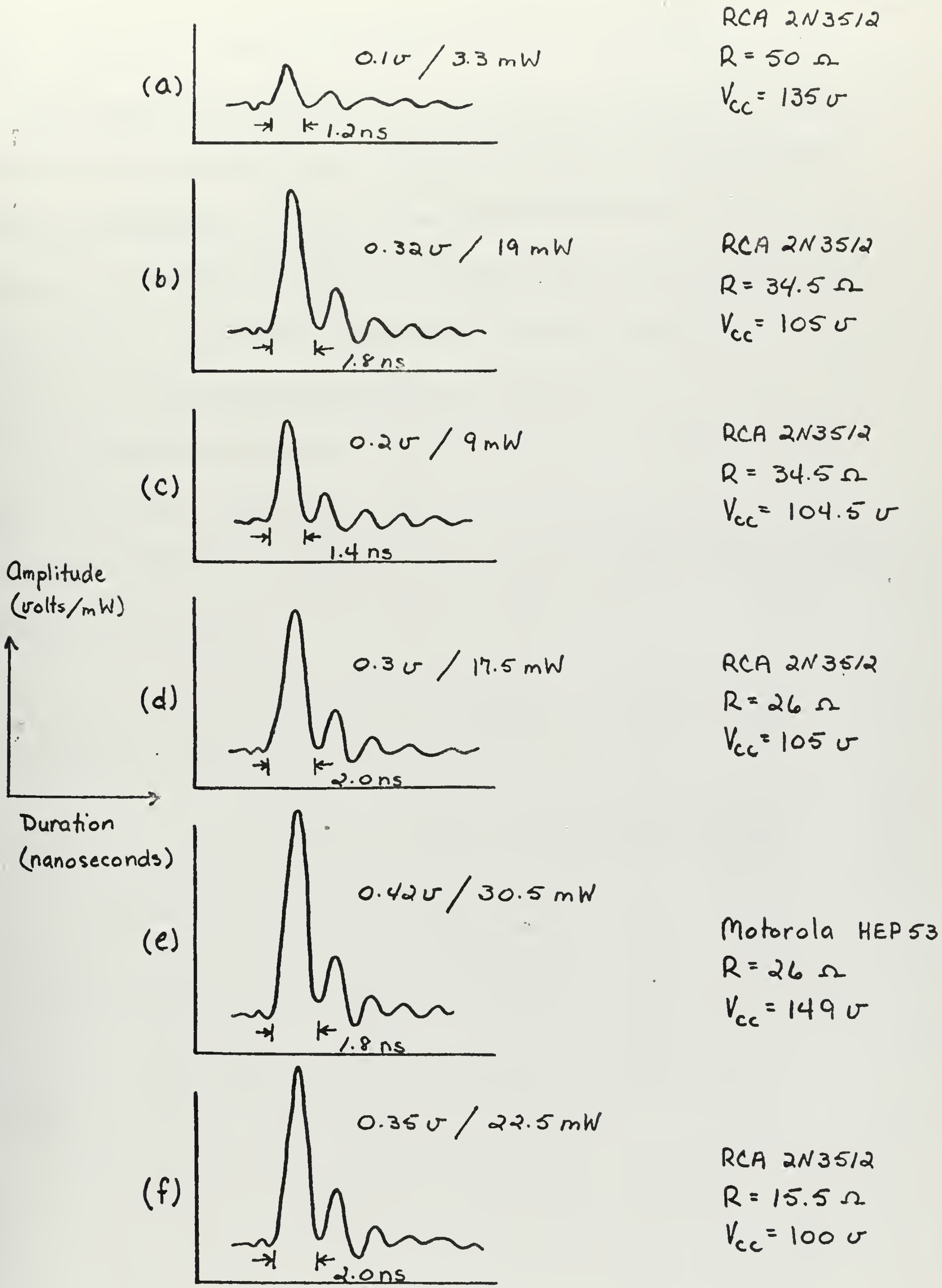


Figure 17. Nanosecond RF pulses.

caused the power to drop by one-half.

One apparent ch racteristic was that as $R_L$ was decreased, $V_{CC}$ had to be reduced and the pulse amplitude increased. This was due to the series arrangement of $R_L$ and the Gunn-effect device. As $R_L$ was decreased, a greater percentage of the total voltage would appear across the device, so $V_{CC}$ had to be lowered. Also the current through the device would increase and this increased the RF out.

The oscillations following the pulses were the result of too much series inductance. The major source of this was probably the contact pin. A different cavity arrangement with a shorter current path is needed to reduce this ringing.

# V. CONCLUSION

The system was capable of producing 1 nanosecond pulses measured at the 3-db points. However, the output power was low and ringing was present. Improvements in the waveguide cavity are needed.

An attempt was made to view the pulses on a spectrum analyzer but unfortunately none of the available equipment had a sufficiently broad passband.

Aside from improved cavity efficiency there are two ways by which the output power could be increased. One is a method reported by Hansen [Ref. 4] using several avalanche transistors in parallel. The other is reduction of $R_L$ below 15 ohms to permit more current to flow.

The system should prove useful in time-domain reflectometry because of the resolution it offers. It is uncomplicated, small and inexpensive.

## APPENDIX A

CALIBRATION CURVES

Since both the circulator and crystal used in the RF pulse detector circuit are frequency dependent they were calibrated as a single unit. The circuit shown in Fig. 18 was used for this purpose. Figure 19 contains the calibration curves for several frequencies.

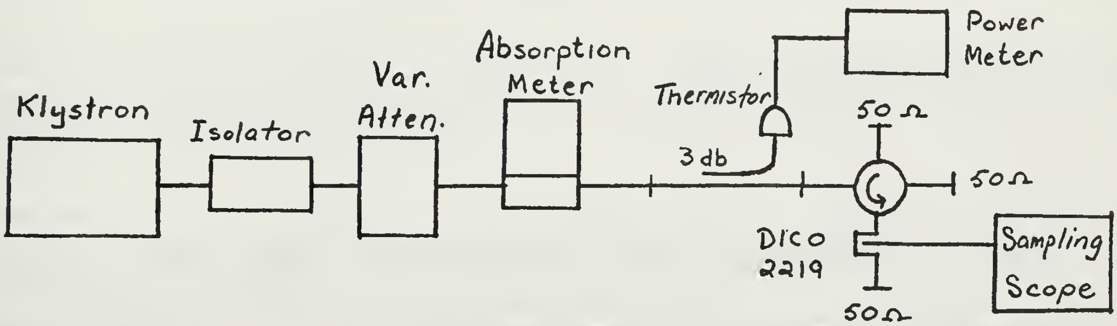


Figure 18. Calibration circuit.

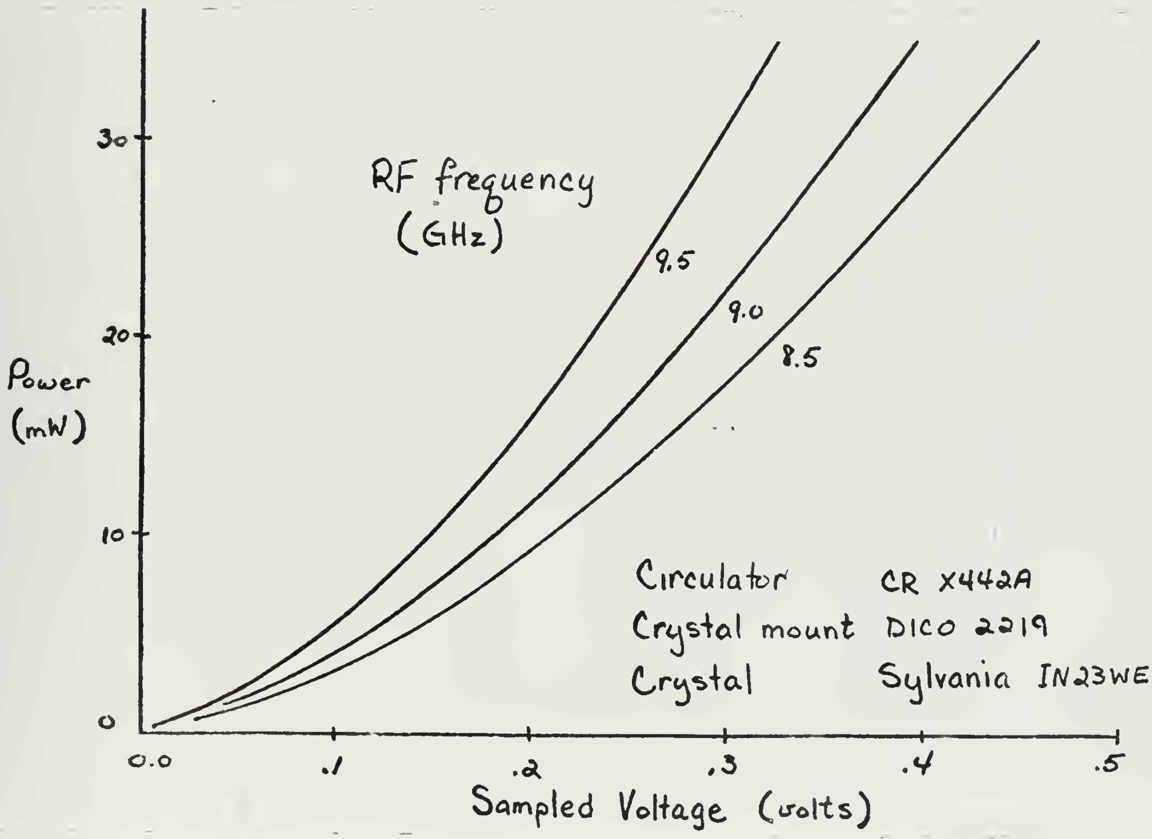


Figure 19. Calibration curves for circular and crystal.

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13. ABSTRACT

A simple circuit has been developed for producing extremely short X-band radio-frequency pulses using a Gunn-effect oscillator and avalanche transistor modulator. Construction techniques and some resulting difficulties are discussed. Representative pulses on the order of 1 nanosecond and 30 milliwatts at 8.5 gigahertz are presented.

This circuit is intended for use in waveguide time-domain reflectometry. The nanosecond pulses offer a large improvement in resolution over previous pulse generation systems.

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| Time-domain reflectometry | | | | | | |
| Avalanche transistor | | | | | | |
| Nanosecond radio-frequency pulses | | | | | | |
| X-band pulse generator | | | | | | |
| Waveguide fault-finding | | | | | | |

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